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Components

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[l'Application des principes de la tolerance a
l'endommagement pour une meilleure aptitude au
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DAMAGE TOLERANCE APPLIED ON METALLIC COMPONENTS

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SUMMARY :

New requirements including damage tolerance were inserted in FAR 29.571, amendment 28 in 1989 to increase the safety level of helicopters.

" Flaw tolerance safe life " and " fail safe " - or a combination thereof, were proposed to fulfil the damage tolerance requirements. If unpractical, " safe life " evaluation was acceptable.

A working group called TOGAA was mandated by the US Senate to propose modifications to the FAA rules. Harmonised recommendations from rotorcraft manufacturers (RCWG) had been gathered in a " White Paper ". The TOGAA commented this methodology and concluded in mid 1998, that the " flaw tolerant safe life " concept should be purged in FAR 29, and advocated the exclusive use of crack propagation for single and multiple load paths.

This paper presents EUROCOPTER's statistical analyses of the root causes of accident in flight. EUROCOPTER's philosophy in reply to FAR & JAR 29-571 is detailed, showing a significant and measurable improvement over conventional " safe-life " methodology. This philosophy has already been applied to several current projects (EC 155, NH 90), and the RCWG simply wanted it to be left in the current rules.

The main technical arguments presented to the TOGAA are set out.

1. BACKGROUND

Fatigue[1] evaluation of metallic parts, the failure of which could have catastrophic effects on the rotorcraft was based till now on the " safe-life " concept. Parts are retired from service at specified times, regardless of their condition.

This service life was determined from analysis or/and fatigue testing performed on full scale as-manufactured[2] components with a high load safety factor (typical 1.4 for gears, 1.8 to 3 for other components as shown in figure 1).

In addition, safety was largely improved by:

- routine visual inspection or preventive scheduled maintenance actions (defined in the Recommended Maintenance Program); these were based either on flight hour intervals to check fretting, wear, loss of tightening torque, impact, scratch, etc. or on calendar intervals to check for corrosion (atmospheric, galvanic or stress).
  These inspection intervals were generally based on previous experience acquired with similar designs and updated according to the behaviour noted during overhauls.

- specific maintenance actions (reported directly to operators or/and approved repair shops).

  These actions (recommended or mandatory) were drawn from the analysis of damages found during overhauls, accidents[3] or major incidents[4] that occurred on the fleet.

- detection of abnormal helicopter behaviour.

Paper presented at the RTO AVT Specialists' Meeting on "Application of Damage Tolerance Principles for Improved Airworthiness of Rotorcraft", held in Corfu, Greece, 21-22 April 1999, and published in RTO MP-24.

Several potentially major accidents or accidents were avoided further to the detection of abnormal helicopter behaviour by an operator (poor blade tracking, leaks, vibrations, noise, etc.) or by the use of a Health Monitoring System equipped with accelerometers and load gages.

New civil regulations FAR 29-571 (Federal Aviation Regulation, Part 29 applicable to rotorcraft over 6,000 lbs = 2,700 kg, structural fatigue evaluation) were introduced to increase the helicopter safety level mandating proof of damage tolerance in amendment 28 date 27 November 1989. Furthermore, an associated Advisory Circular (AC 29-571) was issued in 1995.

No helicopter in the world has yet been fully substantiated according to these requirements.

2. FAR & JAR REQUIREMENTS (including damage tolerance)

The damage tolerance philosophy was developed to eliminate- or at least reduce, fatigue failures affecting components with pre-existing manufacturing quality deficiencies (e.g. inclusion, scratch, flaw, burr, crack, etc.) or service induced damage (impact, scratch, loss of bolt torque, wear, corrosion, fretting corrosion, etc.) that were the root causes of cracking.

The damage tolerance approach is based on the assumption that a damage or a crack in a component can be safely detected before the failure of this component.

In these new requirements, it is now required to consider the effects of environment, intrinsic / discrete flaws and accidental damage in the fatigue evaluation, unless it is established that this cannot be achieved within the limitations of geometry, inspectability or good design practice for a particular structure. (A " safe life " approach should be used in that case).

Two different concepts were proposed to fulfil the damage tolerance requirements :

- FLAW TOLERANT SAFE LIFE
- FAIL SAFE

or a combination thereof.

These concepts are detailed hereafter.

2.1 Flaw Tolerant Safe Life Concert

This is understood as the capability of a flawed structure to sustain, without measurable flaw growth, the spectrum of operating loads expected during the service life of the rotorcraft or during an established replacement time.

2.2 Fail Safe Concept

This is understood as the capability of a structure with a standard crack (Initial Quality Crack) or a detectable crack (using a prescribed inspection plan) to sustain the spectrum of operating loads expected during the inspection interval.

Fail safe design can be provided through different concepts (figure 2).

Figures 3 (single load path) and 4 (2 active multiple load paths) (extracted from AC 29-571) explain how the inspection intervals are set (difference between the time when the damage becomes detectable and the time when the extent of the damage reaches the critical value for residual static strength).

3. EUROCOPTER'S PHILOSOPHY

Some specific tasks were performed by EUROCOPTER to identify the type of damages encountered in service throughout the literature [ref. 1] and the analyses of the root causes of accidents in flight.

The prime results of the survey are roughly summarised below:

- Rate of accident : 37 per million of flight hours (16 of which were fatal).
  (EUROCOPTER average rate of accidents for the last five years on a " world-wide/all mission " basis)

- Reasons for accident :

  - **77%** were due to **operational conditions and environment** (poor estimation of distance with fixed or moving obstacle, poor piloting (weather condition, fuel shortage, non observance of flight manual limitations), wrong behaviour upon non catastrophic events or failures, non qualified pilots (rotorcraft type, weather conditions), pilot's physical inability to performed the required tasks).

  - **17%** were due to **incorrectly performed maintenance** (misassembly, omitting components, non performance of a mandatory modification, assembling of components not-approved by manufacturer, polluted fuel, non detection of a detectable damage, ground personnel errors during movements or rotations).
  - **3.1%** were due to **engine malfunction**.

- **2%** were **pending cause**

- **0.6%** were **non-identified cause**.

- **0.3%** were due to poor design, non conformity of components, poor substantiation, more severe load spectrum usage than expected, non-identified cause of fatigue cracks (cracks generally appearing in high stress concentration areas or otherwise from minor defects which are not the cause but the catalyst of fatigue cracks).

EUROCOPTER estimates that some accidents (less than 20 over 43 millions of flight hours) and major incidents could have been avoided by using the damage tolerance approach.

The causes of these cracks were distributed as follows :

- 30% corrosion (galvanic, atmospheric, stress)
- 25% fretting, wear
- 20% bearing
- 15% flaws (manufacturing or maintenance)
- 10% loss of bolt tightening torque.

Although this survey does not claim to be comprehensive, it can be concluded that wherever conventional " safe life " helicopter methodology is applicable (full-scale fatigue test on as-manufactured parts, in flight load measurement, conservative load spectrum and high load safety factors), it is successful in providing a high reliability.

Important Research & Development programs are in progress to reduce significantly accidents (94%) due to operational conditions and environment (all weather helicopters, improvement of Man Machine Interface, Fly-By-Wire, etc.) and due to incorrectly performed maintenance (Health and Usage Monitoring System, etc.).

Moreover, EUROCOPTER proposes to improve the substantiation of inspection intervals based on :

- flaw tolerant inspection interval
- slow crack propagation
- multiple load paths

Although the wording is similar to the one used in the FAR 29.571 (report to chapters 2.1 and 2.2), EUROCOPTER's philosophy is slightly different and detailed below.

3.1 Flaw Tolerant Inspection Interval

This is understood as the capability of flawed[5] structures to sustain, without measurable flaw growth or fatigue crack initiation, the spectrum of operating loads expected during the established inspection interval.

At the time of the periodic interval, the part may be :

- retired without inspection
- returned to service if no flaw is found
- retired or repaired if a flaw is detected.

The inspection generally is a detailed visual inspection and more (Non Destructive Examination) if a doubt exists.

3.2 Slow Crack Propagation

This is understood as the capability of a single load structure with a detectable (using a prescribed inspection plan) fatigue crack to sustain the spectrum of operating loads expected during the established inspection interval.

At the time of periodic interval, the part may be :

- retired without inspection
- returned to service if no crack is found
- retired or repaired if a crack is detected.

The inspection will generally involve a Non Destructive Examination.

3.3 Multiple Load Paths

This is understood as the capability of a multiple load structure (N load paths) with detectable (using a prescribed inspection plan) failed load path (n) to sustain the spectrum of operating loads expected during the established inspection interval.

At the time of periodic interval:

- if a failed load path is found, all the components of the load path will be retired
- if no failed load path is found, parts may be returned to service

- if some parts are found with flaws, these parts may be retired or repaired individually.

The inspection will generally involve a visual inspection to detect the failure of one load path.

In this concept, full-scale fatigue tests are performed with the remaining load paths (N-n) with as-manufactured parts, and the inspection interval is based on the initiation of a fatigue crack in the remaining overloaded load paths.

As far as new designs are concerned, the damage tolerance aspects have to be considered at a very early design stage.

This is why EUROCOPTER undertook with its own and European funds under the BRITE/EURAM program [ref. 2] a significant research program to fill the knowledge gap in crack propagation theory and in material data base (see figure 5 - crack growth rate versus stress intensity factor range curves).

Although know-how was significantly advanced, the main conclusion was that an industrial methodology fully applicable to helicopters was not available (and probably will not be available in at least 10 years) because data are missing regarding:

- propagation near the threshold region
- effects of load spectrum (retardation, acceleration effect)
- short crack propagation (crack size less than 0.5 to 1 mm in depth)
- mixed mode propagation (tensile, bending and shear stresses)
- fatigue crack path in complex 3D components
- calculation of stress intensity factor by Finite Element Method
- effect of compressive loading
- material data base (near the threshold region)
- reliable safety factors (lack of experience of in-service components designed with crack propagation methodology)

Moreover, the difficulties in practically achieving a slow crack growth design in metallic components of helicopter with a reasonable interval/method are listed hereafter:

- small component size
- high number of cycles per hour (typical 15,000 for main rotor components , 60,000 for anti-vibration system components, 75,000 for tail rotor components, 300,000 for tail rotor control components, 60,000 to 1,300,000 for rotating shaft components)
- highly stressed with alternative loads
- large crack size surely detectable in the field (table 1) often induces to a short propagation time
- Once the fatigue crack propagates, the stiffness of the component changes, and the dynamic loading of the part on the rotorcraft may be changed (but will never be measured in flight).

In conclusion, a slow crack growth could be achieved for a few components only:

- components which are mainly loaded by Ground-Air-Ground cycles (1 to 10 cycles per hour)
- components already oversized (minimum technological thickness, stiffness requirements, ...)
- component the features of which (pressurised chamber, vibration sensor, etc.) surely could detect cracks, with a low false alarm rate.

Meanwhile, EUROCOPTER undertook with its own and French government funds a significant test program to deal with flaw tolerant inspection interval methodology.

Three of the most critical damages (corrosion, scratch and impact) were selected. For each of them, a statistical analysis of sizes found during overhauls was performed. The results are dependent on the type of material used (figure 6).

A standard damage per material had been defined for each type covering 90% of the damage encountered during the service life.

Fatigue tests were performed on specimens with these standard damages on different kinds of material (steel, stainless steel, titanium, aluminium alloy, magnesium alloy).

Figure 7 shows the influence of 0.15 mm deep scratch on steel parts.

Moreover, in the " flaw tolerant inspection interval " concept, the protection of structures against flaws (via characteristics of the material, protective coating, anti-damage shield, etc.) may be used to determine the initial flaw types and sizes to be considered.

Design efforts were made to prevent flaws in the NH 90 helicopters (figure 8) in particular:

- critical components usually made of steel (rotor hub, sleeve, screws,...) are now made of titanium, or stainless steel to prevent corrosion.

- deposits resistant to fretting or wear have been applied on most critical interfaces.

- the number of bearings has been limited to a minimum by using super-critical tail rotor drive shafts or spherical elastomeric thrust bearings.

Finally the authorities approved for NH 90 (figure 8) and EC 155 (figure 9) the damage tolerance qualification program based on both conventional safe life (initiation of fatigue crack using as-manufactured component) and repetitive inspection intervals based on one of the 3 equal concepts (flaw tolerant inspection interval, slow crack propagation and multiple load paths).

4. TOGAA/RCWG

Meanwhile in the USA, a working group called TOGAA(6) was required by the US Senate to give some thoughts to the general tolerance to damage of fixed wing aircraft problem, with the possibility to propose some modifications to the FAA rules. Following discussions with fixed-wing aircraft manufacturers and FAA/JAA, this group proposed a new FAR 25-571 paragraph related to fatigue evaluation.

From 1993 onwards, the TOGAA discussed with the helicopter manufacturers and requested in 1997 that the RCWG(7) provide the TOGAA with a " White Paper " on fatigue and damage tolerance that would form the basis for a revision of Advisory Circular AC 29-571, and possibly FAR 29-571, if warranted.

After a very constructive co-operation with the US and European manufacturers, a harmonised methodology for fatigue and damage tolerance focusing on metals was found and a " White Paper " was prepared and submitted to the TOGAA for comments.

The following technical arguments were developed to cope with potential questions or concerns:

1. How undetectable or barely detectable flaws are covered by manufacturer methodology ?

Intrinsic material defects and manufacturing defects should be covered as follows:

- Intrinsic material defects (inclusions)

  Intrinsic material defects which are undetectable or barely detectable by reasonable industrial means could be substantiated by a combination of statistical approaches based on the probability of occurrence of the damage, severity of the damage demonstrated by tests, analysis or in-service experience and stress level applied on the part in service.

  EUROCOPTER experience of cracks initiated from intrinsic material defects (table 2) shows that type of material, inclusion class for steel and load safety factors are of prime importance.

- Manufacturing defects

  Potential manufacturing defects can occur upon every step of elaboration (semi-finished products, blanks, machining, heat treatment, anti-corrosion process, inspection, welding, etc.).

  As far as critical components are concerned, EUROCOPTER past experience of elaboration involved freezing the essential manufacturing parameters (i.e. cutting or grinding conditions, type of tools, cutting speed, part clamping, etc.), high quality controls and traceability.

  Moreover, process and inspection methods are continually improved. Examples of improvement are listed below :

  - elimination of sensitive processes such as black oxidising, chemical etching,

  - use of nitriding, shot-peening for compression near the surface of the component,
  - degassing treatment to avoid hydrogen embrittlement,

  - nital etching to detect grinding cracks,

  - microfocus to inspect welded joints

  In addition, destructive inspections are performed after full-scale fatigue tests on as-manufactured components to check for any defect originating the crack.

  This expensive procedure helps ensure that the serial parts shall be produced with the same process used for fatigue evaluation, including eventual pre-existing cracks resulting from the process itself, if any.

A conventional safe life with conservative working curves accommodates the occasionally very small flaws.
Our experience regarding flaws of this size is that they had little or no effect and could be detected once they were big enough to have an effect.

In conclusion, EUROCOPTER considers that the use of material with better inclusion cleanliness related to in-flight stress level, the freezing and traceability of elaboration and inspections (continually improved by experience) of critical components, on the one hand, and the use of conservative working curves, on the other hand, should accommodate the occasionally very small flaws much better than in the past.

2. How flaw types and sizes are selected?

The flaw types and sizes imposed to each component are submitted with a rationale to the authorities for approval.

The types of flaw that are systematically considered should include scratch, corrosion, fretting, wear and loss of bolt torque.

These flaws should have the maximum size that can be reasonably expected during the service life.

A Consensus between the industry and the authorities should be easily found for selecting standard flaw type, size and geometry as done in the past for accelerated ageing and definition of impacts on composite components.

3. Can the successful experience from fixed-wing aircraft using crack propagation methodology be transposed to helicopter ?

Regarding the success of fixed-wing aircraft certification exclusively based on crack propagation, a synopsis of some differences between helicopter and fixed-wing aircraft is presented in table 3.

The main reason for this success is mainly load frequency and the detectable crack size large enough to be reliably detected.

This success is all the more emphasised as cracks in service occur on a very large fraction of aircraft components.

This poor experience may be due to poor choice of allowable (load safety factor equals to 1.15 for fixed wing compared to typical 1.8 to 3 for helicopter) and inadequate control of component quality related to fatigue.

In conclusion, the success of fixed-wing aircraft certification based on crack propagation can be explained but cannot be transposed to helicopter due to its specificity (high load frequency and detectable crack size).

4. Can the past manufacturer experience of crack propagation methodology be generalised to all the components of helicopter ?

Manufacturers already used crack growth analyses and tests to solve service cracking problems.

However inspection intervals, deduced from microscopic observations of the failure of the component, are often short. These constraints and overcosts are generally accepted by the operators because the action is temporary and the manufacturers are looking for a final solution at fleet level.

Moreover, the method of inspection is particularly suitable to the problem and the operators specially careful.

Finding a known crack in a precise location on a particular part is one thing, but finding an improbable small crack somewhere in every critical component of a helicopter is another.

In addition to the unavailability of a full and reliable methodology for crack growth applicable to helicopters, and to the difficulties inherent to obtaining a reasonable interval/method, the manufacturers feel uncomfortable with having the reliability (and liability) of a part depends on the success of individual helicopter operators finding small cracks.

In fact, the detection of cracks larger than the detectable size is not a certainty, as it is affected by many factors, namely the geometry of the component, material, skill of the operator, specificity of the task, accessibility, Non Destruction Examination process (i.e. X-ray, Eddy Current, Ultrasonics, dye penetrant, etc.) and environmental factors (corrosion, painting...).

Finally, manufacturers are very pessimistic regarding the issue of a lawsuit between an operator and a manufacturer, if detectable cracks were not detected and an accident resulted.

The " White Paper " was presented by the RCWG to the TOGAA during a meeting held in Monterey, California in March 1998,then, during a final meeting held in Lake Oswego, Oregon in January 1999 [ref. 4].

The TOGAA commented the harmonised manufacturer philosophy (ref. [3]) as follows:

- The use of " fatigue flaw tolerant inspection interval " as a repetitive inspection interval was discussed.

- The use of as-manufactured components for the establishment of a safe life or repetitive inspection for multiple load paths was commented.

- The exclusive use of crack propagation for single and multiple load paths was advocated.

- The recently revised AC & FAR 25-571 for large transport fixed wing aircraft was proposed to be the convenient starting point for the future revised rotorcraft AC & FAR 29-571.

5. CONCLUSION

A survey was performed by EUROCOPTER to identify types of damages encountered in service and root causes of accidents in flight.

For the last five years on a « world-wide/all mission » basis , EUROCOPTER average rate of accidents is 37 per million of flight hours.

Important Research & Development programs are in progress to reduce significantly accidents due to operational conditions and environment (77%) (all weather helicopters, improvement of Man Machine Interface, Fly-By-Wire, etc.) and due to incorrectly performed maintenance (17%) (Health and Usage Monitoring System, etc.).

EUROCOPTER estimates that less than 20 over 43 millions of flight hours could have been avoided by using the damage tolerance approach.

The RCWG prepared at the TOGAA request a « White Paper » on fatigue and damage tolerance based on both safe life (initiation of fatigue cracks using as-manufactured components) and repetitive inspection intervals demonstrated with one of the three equal concepts (flaw tolerant inspection interval, slow crack propagation and multiple load paths).

The advantage of this pragmatic approach, already approved by the authorities for EC 155 and NH 90, is to improve what exists today, i.e. the substantiation of inspection intervals with tests and/or an analysis formerly based on experience.

This philosophy was discussed with the TOGAA which advocated the exclusive use of crack propagation for single and multiple load paths.

To date (end of February 1999), final agreement of « White Paper » is pending.

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GLOSSARY

(1) **Fatigue** : fatigue is the progressive process of crack initiation of a part due to the repeated application of varying amplitude loads, any one of which will not produce failure.

(2) **As-manufactured** : As-manufactured condition of a component which is produced by the nominal performance of manufacturing processes specified for that component

(3) **Accident** : accident with loss of life, hull damage, full or partial destruction of the rotorcraft

(4) **Major incident** : Every malfunction which could interrupt, cancel or delay significantly the mission or endanger the crew (loss, failure or damage of critical safety components, use of emergency procedures (engine failure, abnormal heating that might start a fire)).

(5) **Flaw** : A localised defect or anomaly related to manufacturing or service use.
In metals this includes corrosion, fretting, nicks, dents, scratches and gouges, ...
In assemblies, this includes loss of bolt torque, ...

(6) **TOGAA** : Technical Oversight Group for Ageing Aircraft

This group, composed of high level figures from the US aerospace community, was created in 1989 following ALOTA AIRLINES BOEING 737 accident as a result of ageing problems.
Beginning with fixed wing aircraft, the TOGAA expanded to include engines and rotorcraft. The TOGAA mission is to review every age related safety issues and make recommendations to implement corrective actions.
As part of this mission, the TOGAA has expressed concerns regarding the current FAR 29-571 (Rotorcraft fatigue evaluation) and the associated Advisory Circular.

(7) **RCWG** : Rotorcraft Community Working Group.

This group, composed of representatives from the major helicopter manufacturers in the United States and Europe, from the US (FAA) and European (JAA) airworthiness authorities and operators, was appointed to facilitate communication with the TOGAA.

REFERENCES

[1] A survey of serious aircraft accidents involving fatigue fracture
Aeronautical note NAE-AN-8-
NRC NO.21277

[2] BRITE/EURAM " DAMTOL "
Contract n° BREU-0123
DAMAGE TOLERANCE OF HELICOPTER METAL PARTS (1990-1993)
EUROCOPTER DEUTSCHLAND (prime contractor)
EUROCOPTER, AGUSTA, WESTLAND

[3] TOGAA comments on the " white paper " dated April 13, 1998

[4] " white paper " – final issue
prepared for the TOGAA in January 1999
available from Thierry Marquet
thierry.marquet@eurocopter.fr

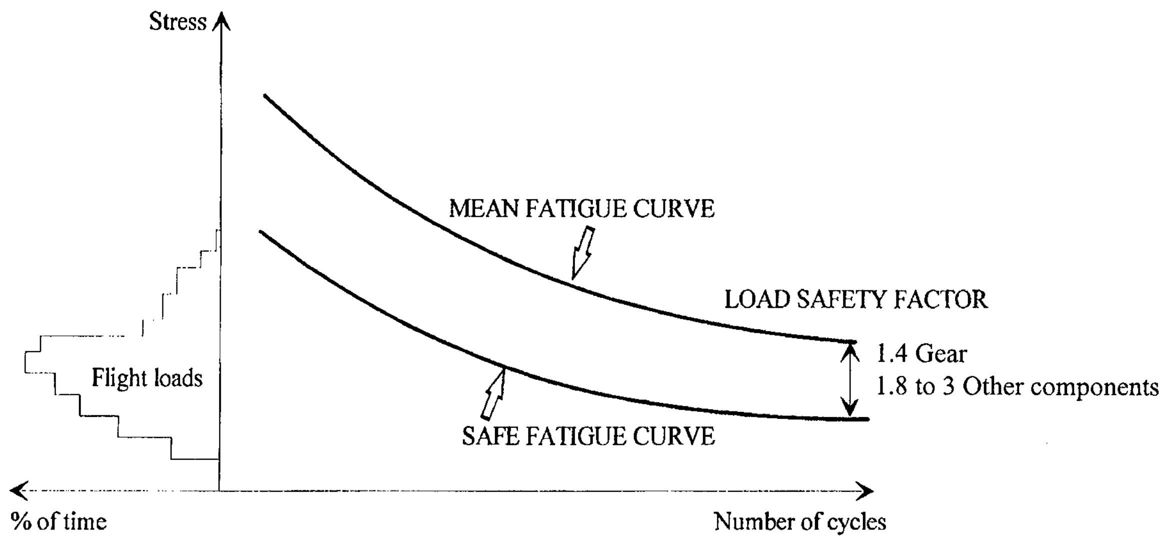

Figure 1 : Eurocopter Safe Life Substantiation Philosophy

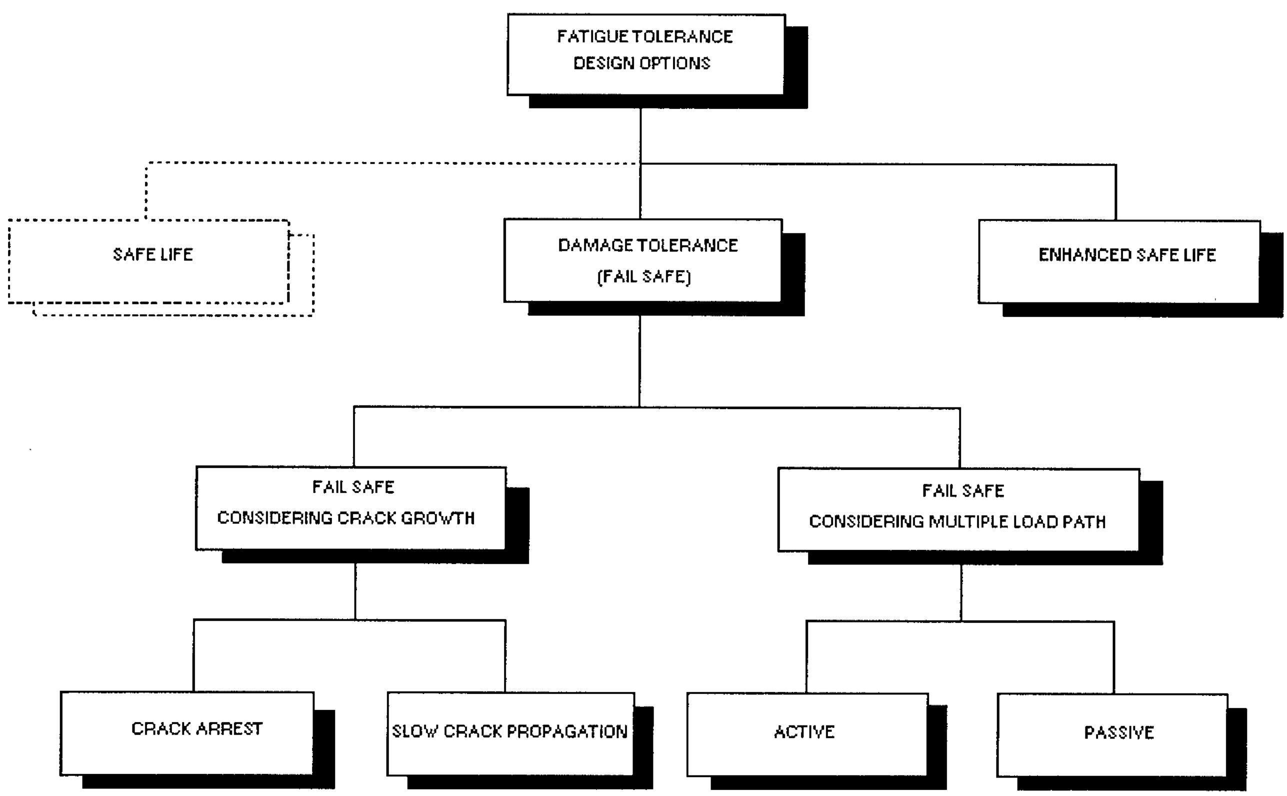

Figure 2 : Fatigue Tolerance Design Options

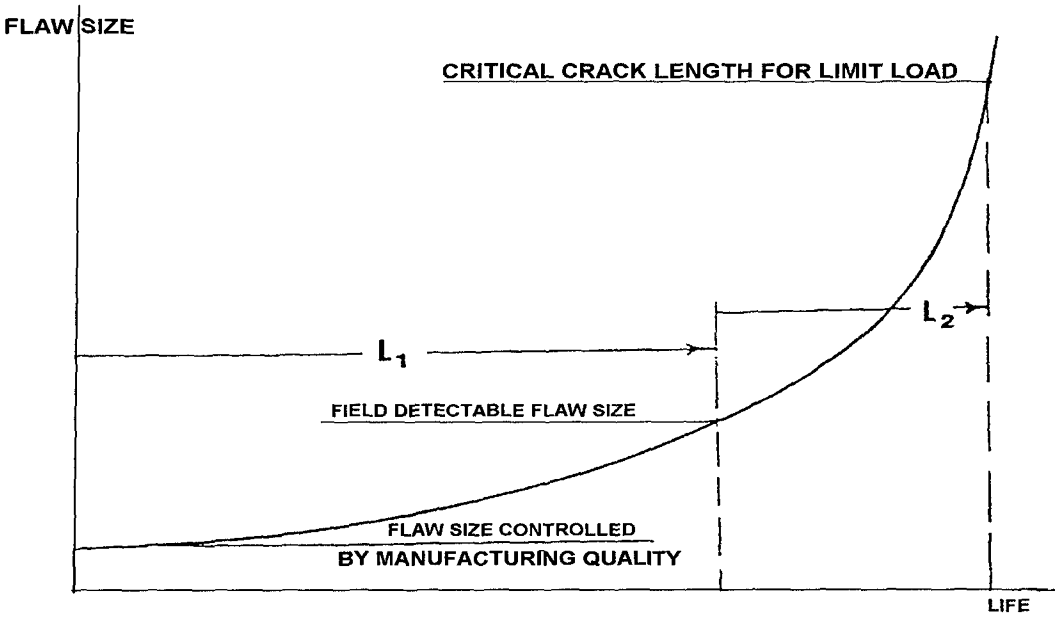

Figure 3 : Crack Growth for Single Element Structure

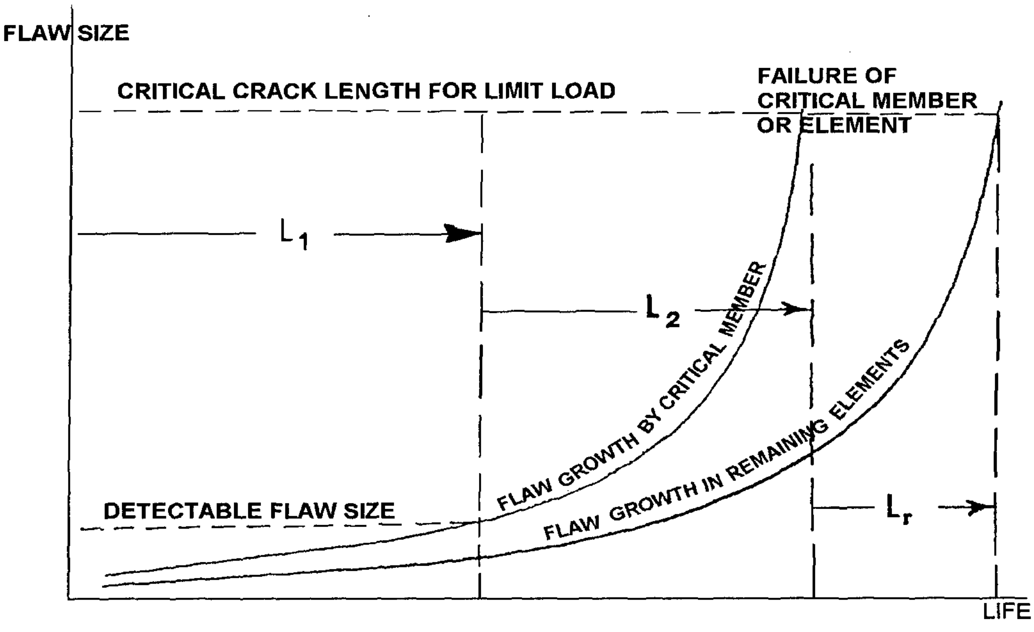

Figure 4 : Crack Growth for Remaining Elements of Multiple Element Structure

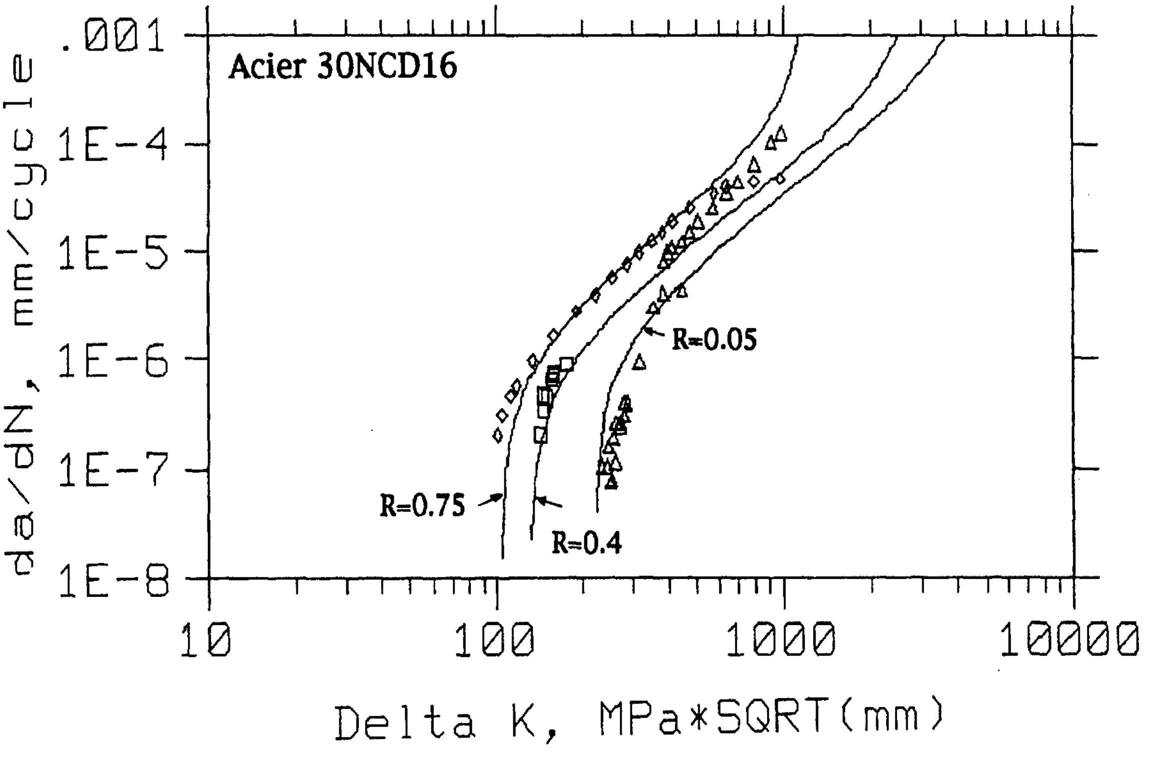

Figure 5 : Crack Growth Rate Versus Stress Intensity Factor Range for 30NCD16 (High Strength Steel)

FIELD DETECTABLE CRACK SIZE DETERMINED BY EC QUALITY DEPARTMENT, WITH A SAFETY LEVEL OF 95 % :

MAGNETIC PARTICLE	**3.6 MM**	**0.14 INCH**
DYE PENETRANT	**4 MM**	**0.16 INCH**
ULTRASONIC	**6 MM**	**0.24 INCH**
EDDY CURRENT	**6 MM**	**0.24 INCH**
VISUAL INSPECTION ON BRIGHT PAINTING	**15 MM**	**0.60 INCH**
VISUAL INSPECTION ON DARK PAINTING	**30 MM**	**1.20 INCH**

Table 1 : Reliable Field Detectable Crack Size

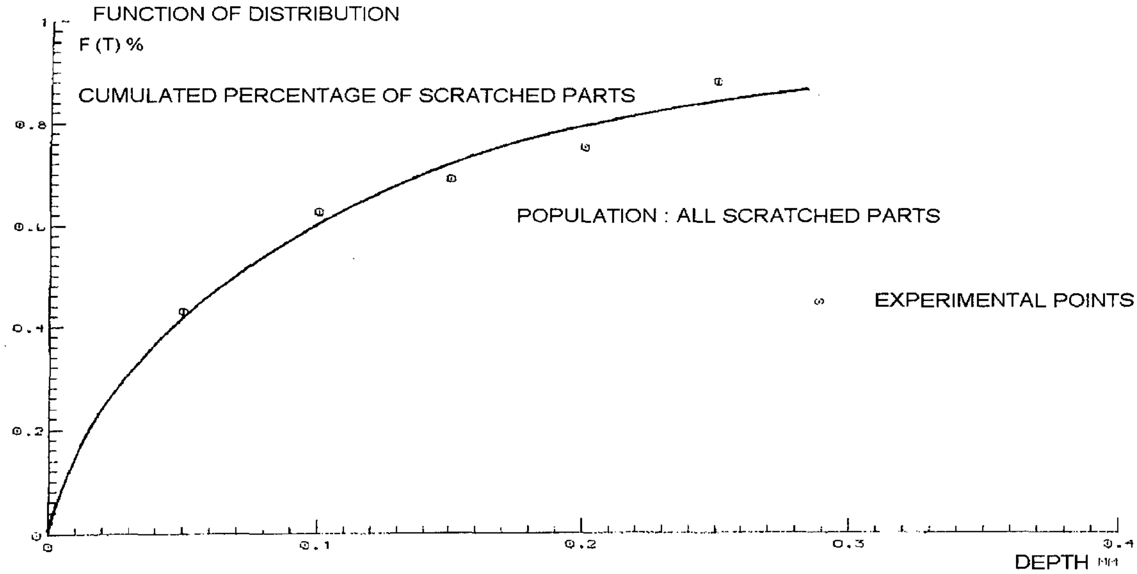

Figure 6 : Statistical Distribution of Scratch Depths Over Steel Parts

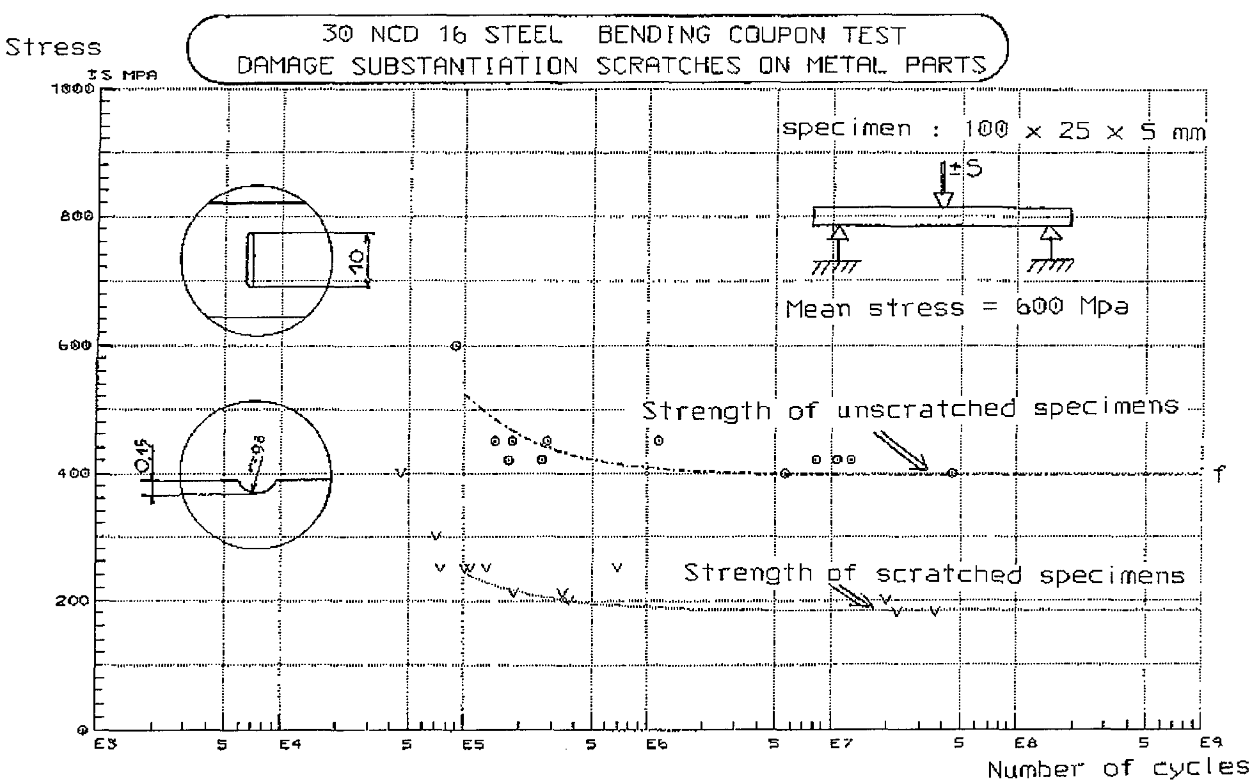

Figure 7 : Fatigue Curve on Flawed Specimens

Figure 8 : NH 90 (Medium Heavy Helicopter)
(EUROCOPTER, AGUSTA, FOKKER)

Figure 9:- EC 155 (Medium Helicopter)

(EUROCOPTER)

		STEEL		ALUMINIUM ALLOYS	TITANIUM
		Class 2	Class 3 or 4		
STRESS LEVEL	Gear teeth of pinions substantiated with load safety factor of 1.4	Several	None	/	/
	Other components substantiated with load safety factor of 1.8 to 3	None	None	None	None

Table 2 : Eurocopter in Service Experience of Material Defects Representative of 43 Millions of Flight Hours (12/97)

Type	Load Cycle Rate	Fatigue Origins	Structure	Loading	Number of cracking structures	Typical Minimum Crack Length Considered
Large Transport Aircraft	1 to 200 cycles per hour	Frequently Multiple cracks on one component or one crack on multiple identical components	Multiple Identical components	Large Areas Identically Loaded	Large Fraction of the Fleet	15 mm (≈ 0.6 inch) to more than 100 mm (≈ 4 inches)
Helicopter	10,000 to 1,500,000 cycles per hour	Single crack on single component	single or a few components	Significant Load Variation Over Small Areas	Extremely Remote	4 mm (≈ 0.15 inch)

Table 3 : Fixed Wing / Helicopter Comparison